SeaQuest Academy: Resonant Extraction

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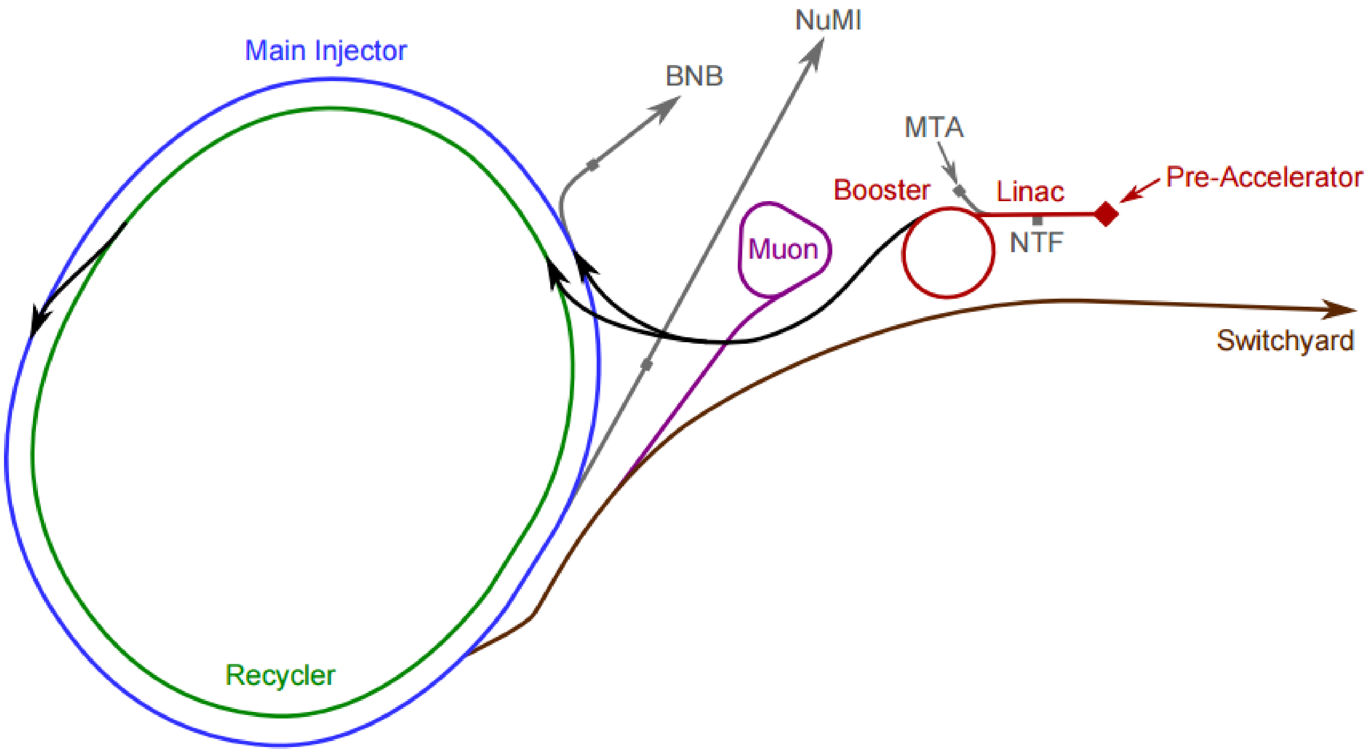
SeaQuest Academy
Day Month Year

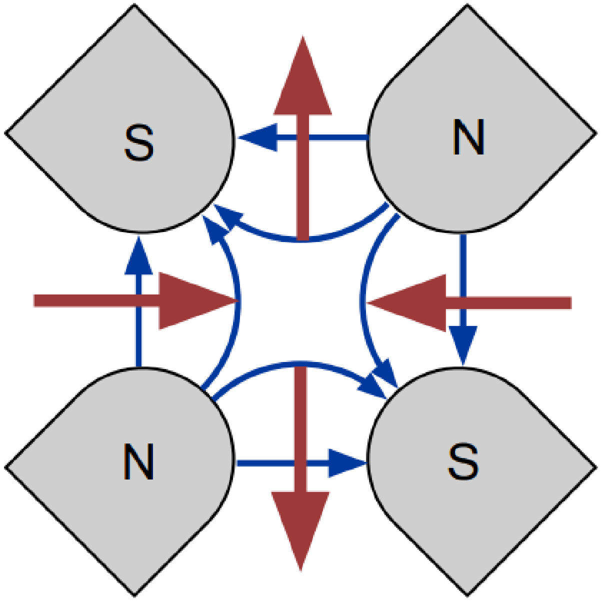
Fermilab Accelerators Overview

Beam created by the Pre-Accelerator accelerates through Linac, Booster, and Main Injector before extraction to Switchyard.

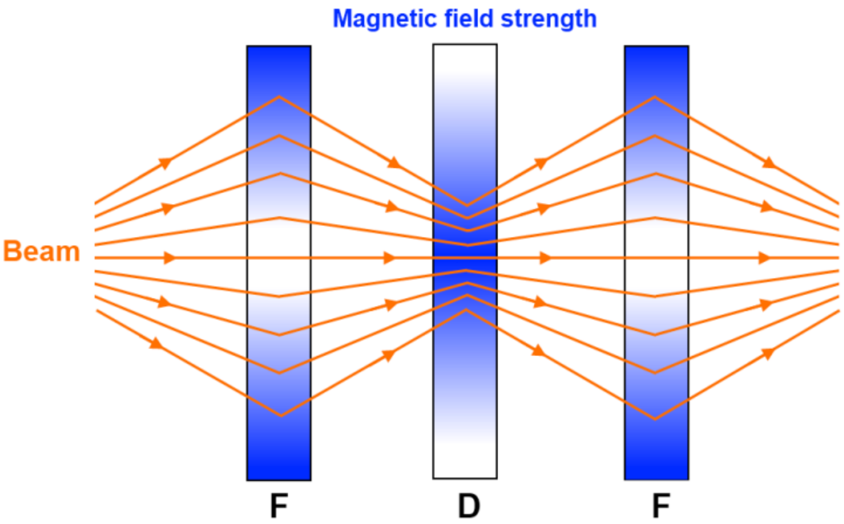


Quadrupole Magnets

Quadrupole magnets act as linear lenses, focusing in one plane and defocusing in the other. Net transport is achieved with a periodic structure of quadrupoles, known as “strong focusing”.



Quadrupole magnet: field lines are blue, force lines for positive charge particle in red

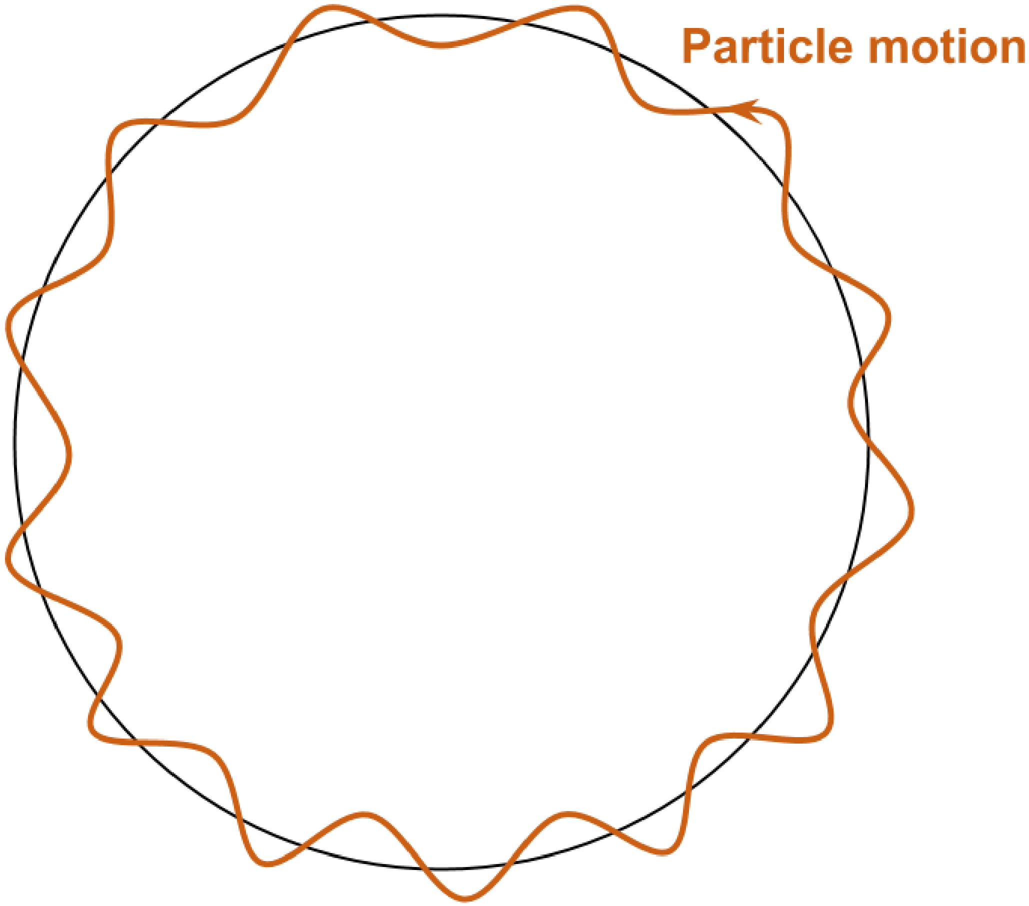


Alternating gradient focusing, a.k.a “strong focusing” provides stable transport of beam over long distance.

Betatron Motion

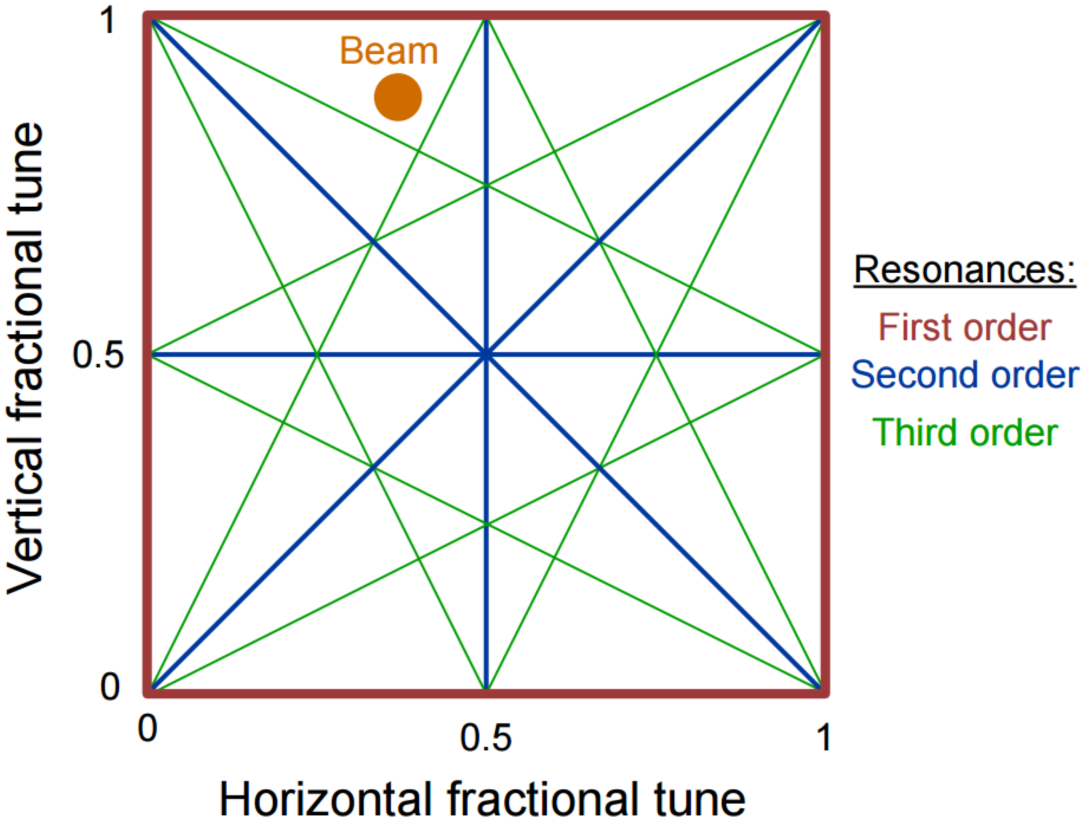
Alternating focusing/ defocusing pattern (“lattice”) in a circular accelerator creates transverse oscillation of particles known as “Betatron motion”. The number of oscillations per revolution is called the “tune” ν.

Since the quadrupole strength depends on the particle momentum, the tune is a momentum-dependent quantity.



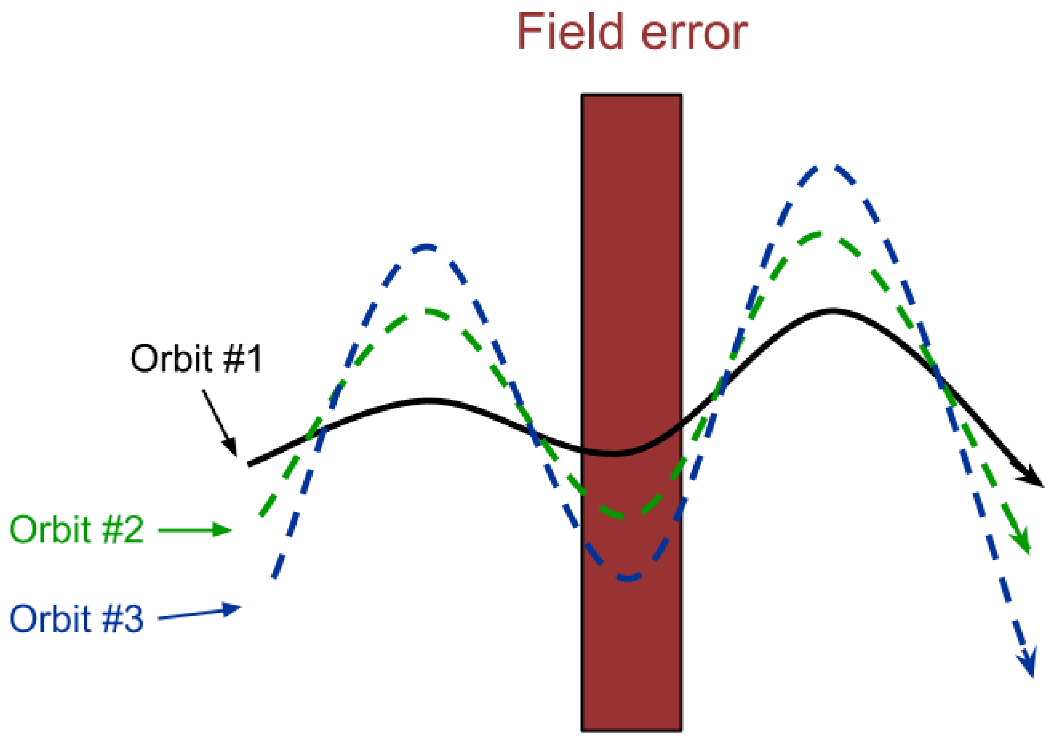
Betatron Resonance

As with any driven oscillation, betatron motion is susceptible to resonance conditions. In particular, fractional-integer tunes allow sensitivity to nonlinear magnet fields in ring; these can be deliberate (sextupoles, octupoles), field imperfections in magnets, or alignment errors.



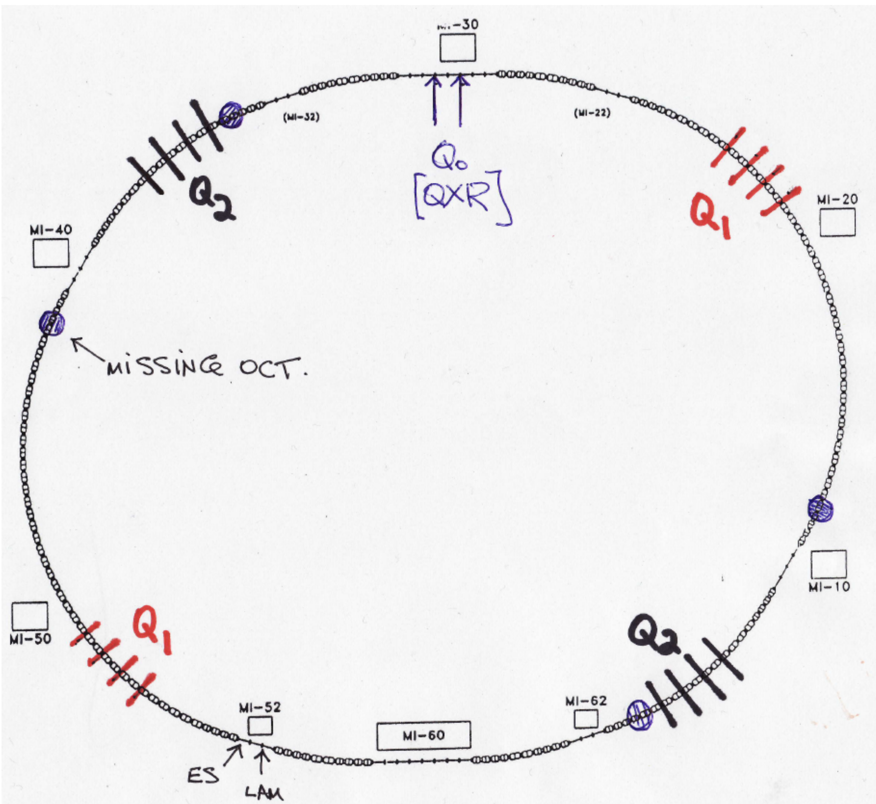
Resonant Extraction

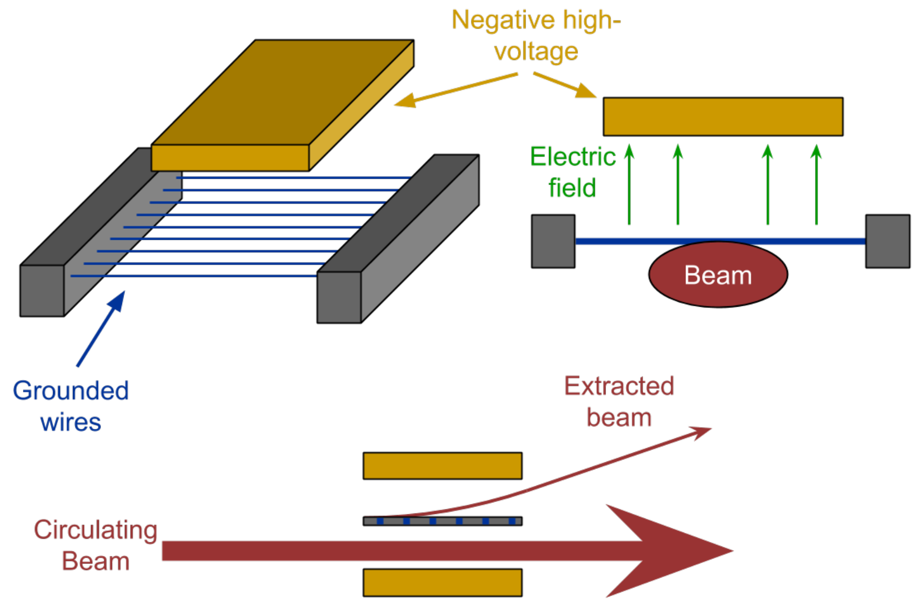
We can leverage betatron resonance to effect a slow extraction out of the synchrotron. In Main Injector, traditional extraction would produce a ~11 μs beam pulse. By causing the beam to undergo betatron resonance and “spill” out of the machine, we can slowly extract the same intensity over 4 s.



MI Half-integer Resonant Extraction

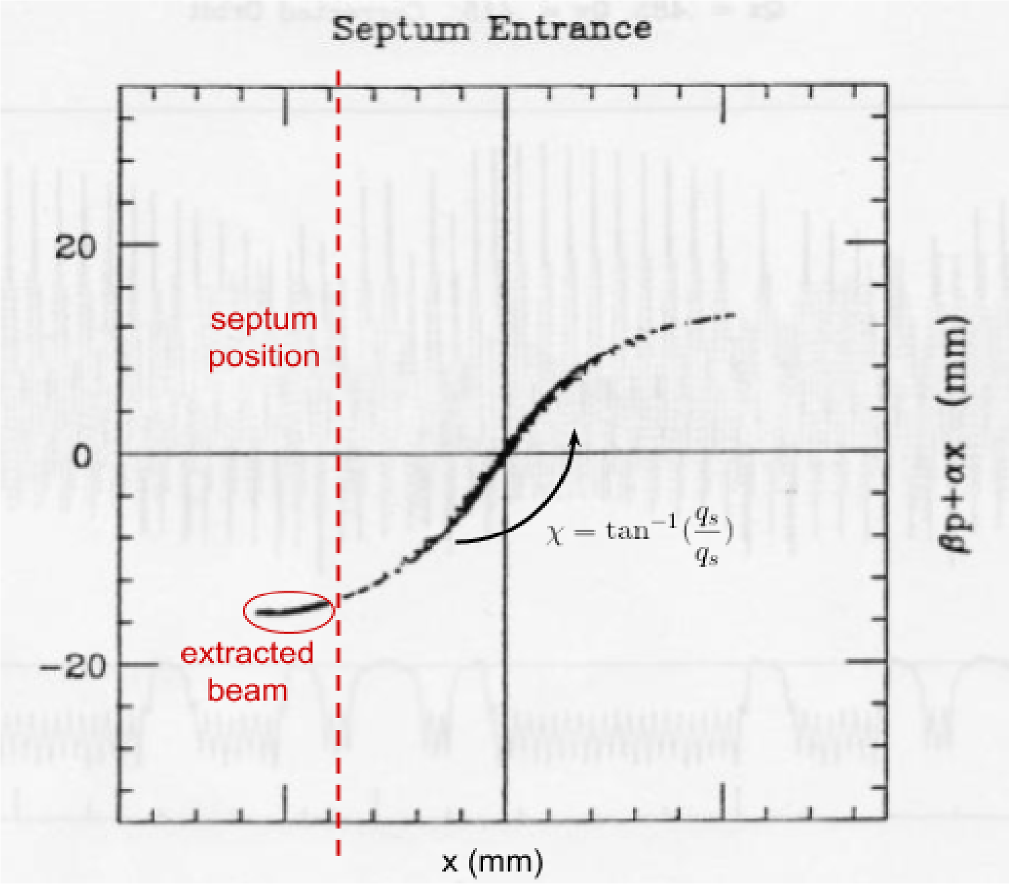
In the Main Injector, we operate with a horizontal tune of 26.5 to increase resonance susceptibility to quadrupole driving forces. Two special-purpose families of “harmonic quadrupoles” drive the half-integer betatron resonance to gradually expand the transverse size of the beam. As particles reach a horizontal orbit deviation threshold (~13mm) at the MI-52 region, an electrostatic septum splits the particles out of the ring and into Switchyard.





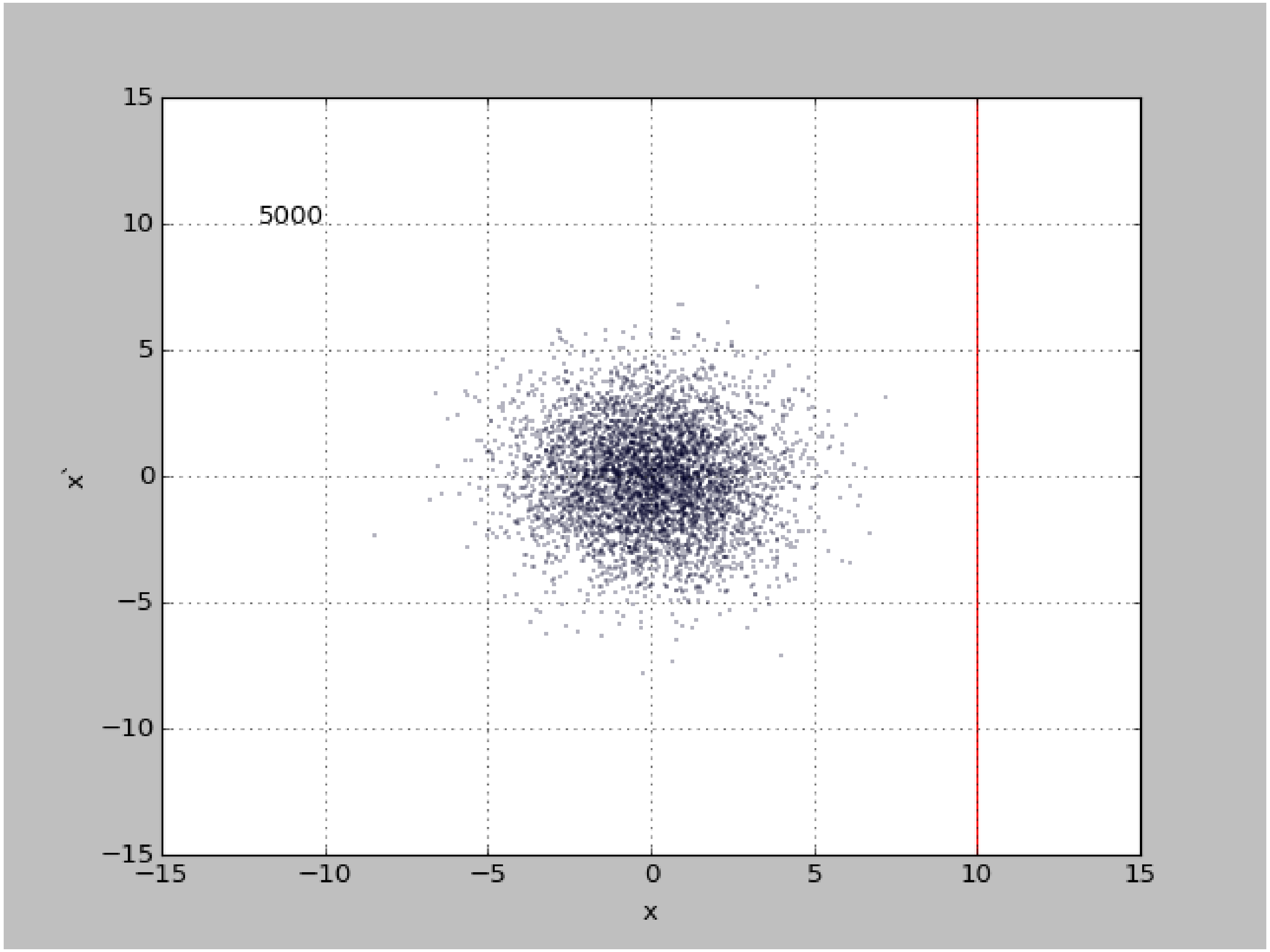
Source: John Johnstone

Transverse phase space



Source: John Johnstone (adapted)

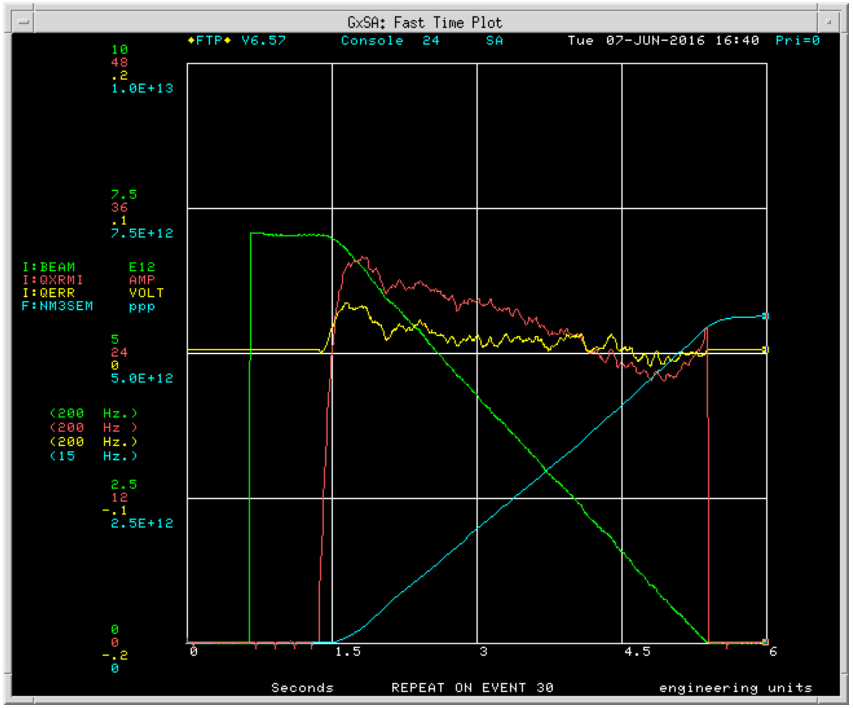
Transverse phase space animation



Slow-spill Regulation

To provide a spill that is as linear as possible, we use a pair of small quadrupoles to nudge the tune up or down as needed during the spill. This regulation system is known as “QXR”, i.e. “Quadrupole Extraction Regulation”, and employs real-time feedback and feedforward learning to improve spill linearity.

One of the QXR quadrupole magnets that regulates the spill by adjusting the tune



Beam spill to SeaQuest and QXR regulation.

Problem:

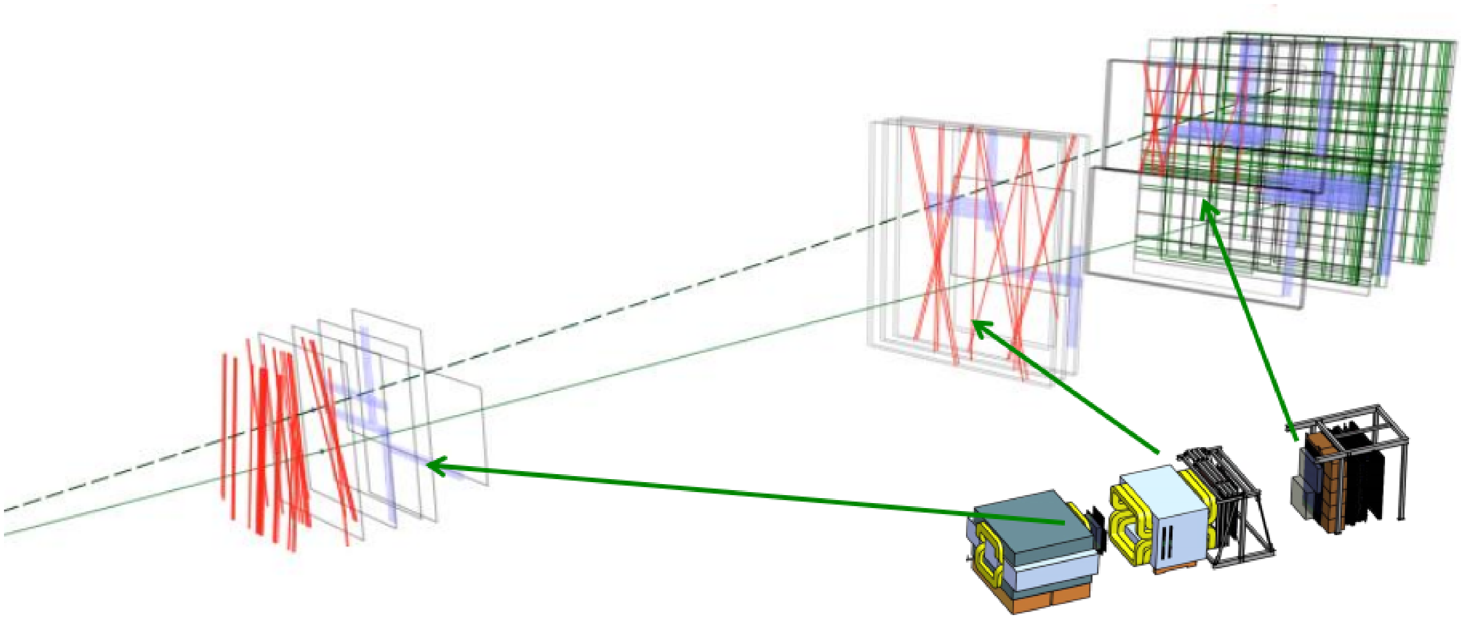
Duty factor

Proposed solution:

More beam fuzzing

SeaQuest duty factor and beam splat

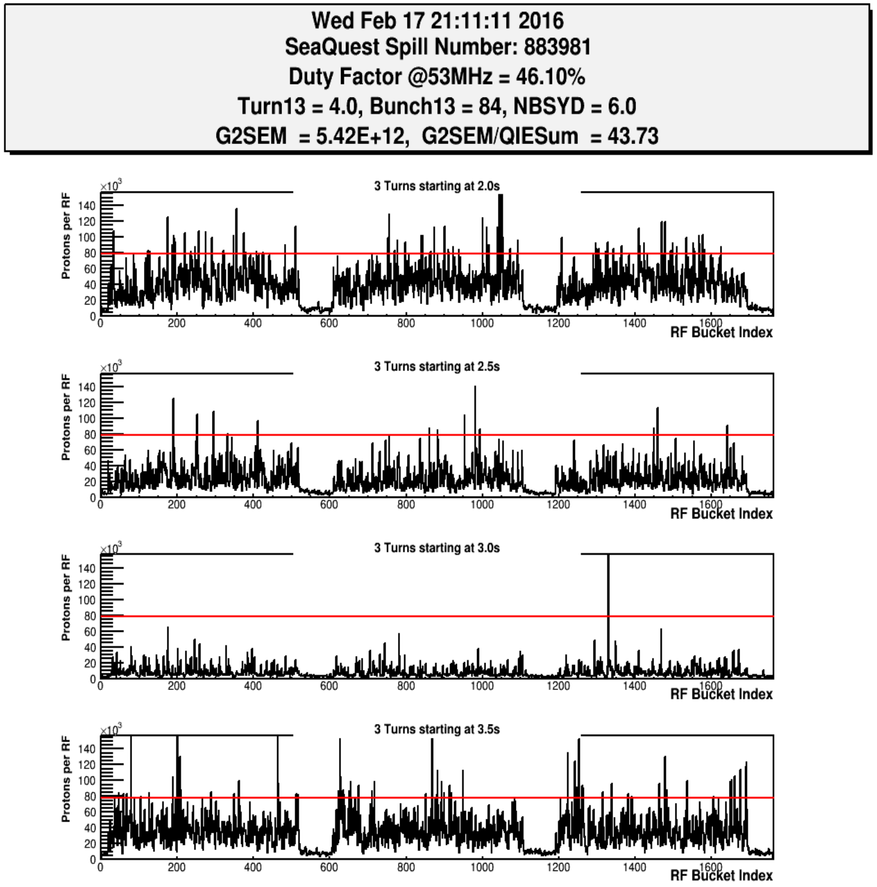
- SeaQuest tracks muon-antimuon pairs produced from their targets: excessive events render tracking impossible
- Uniform intensity throughout the spill is paramount. Bunches with too-high intensity must be rejected, i.e. "beam splat" events

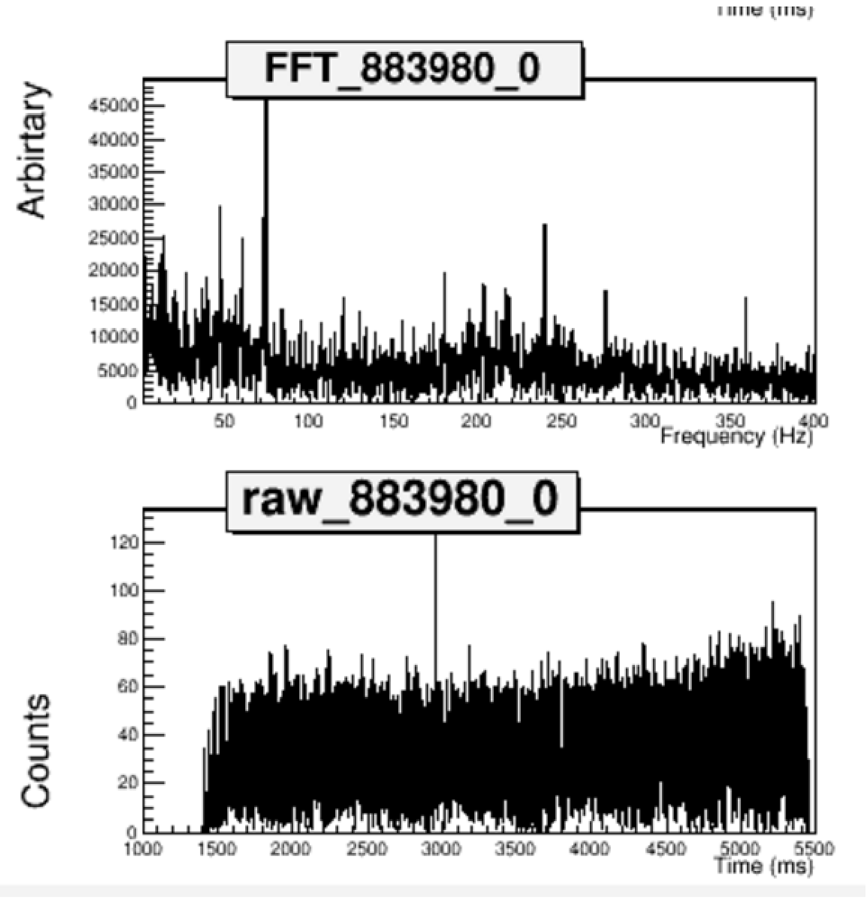


Source: Paul Reimer, 2014

SeaQuest duty factor and beam splat

- Noise from MI quadrupole power supplies contribute to non-uniformity of spill





Source: SeaQuest E906 spill viewer

MI quadrupole bus noise

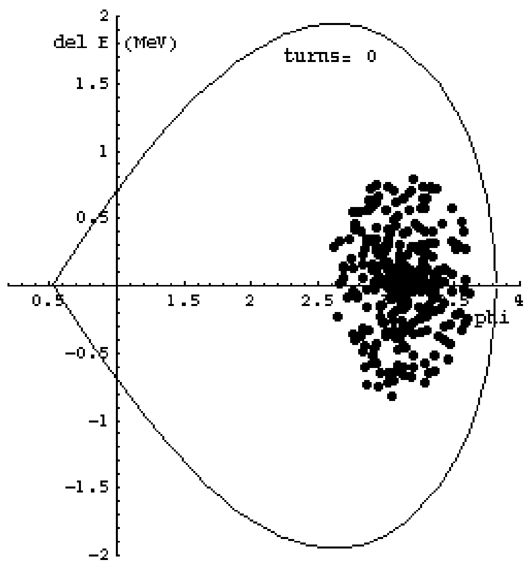
- Tevatron slow-spill duty factor was >>90%: at flat-top, only 1 power supply necessary to maintain bus current, easy to regulate
- MI flat top: 6 quadrupole power supplies to maintain quadrupole currents (3 H, 3 V)
- Phase noise from MI quad supplies very stochastic; filtering is prohibitively expensive, cannot feed-forward (Prieto's talk, bucker usage)
- A spill less dependent on the tune should not “see” this quadrupole noise as much on the spill structure (see transverse knockout)

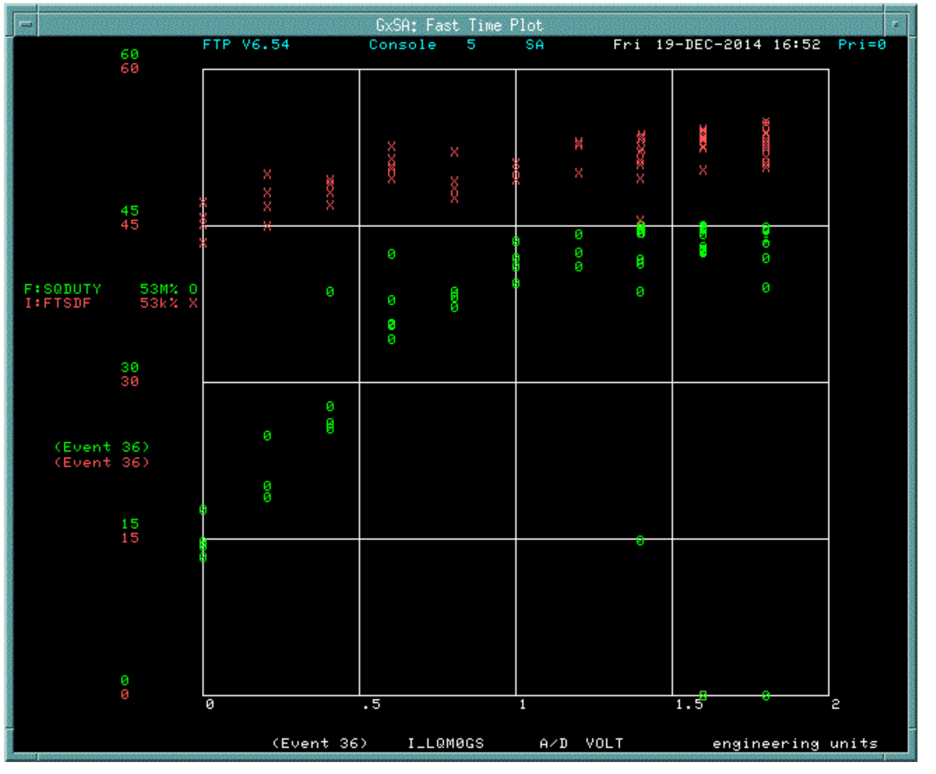
Spill Linearity Limitations

- QXR can only change quadrupole current so quickly, so it has limited regulation bandwidth (i.e. ~kHz)
  - A faster, frequency-domain version of QXR called the “Bucker” has been commissioned to increase the spill linearity at higher frequencies (~100 kHz).
- Random phase noise between the 7 main quadrupole power supplies modulate the horizontal tune, spilling out beam unevenly and also decreasing spill linearity.
  - This phase noise is not repeatable, so feedforward learning in QXR and the Bucker cannot alleviate its effects on the spill structure.
  - *This noise is our most significant bottleneck to higher duty factor*
  - Power supplies are behaving within specifications. Our best bet is to decrease the spill's sensitivity to these inevitable fluctuations.
- Fast coherent motion in the beam due to other resonant instabilities can cause chunks of beam to spill out at once, decreasing the spill linearity.
  - “Fuzzing” the beam has shown promise in smoothing out coherent instabilities that affect the spill structure

Longitudinal “Fuzzing”

Main Injector department installed a system that oscillates the accelerating voltage during the second half of the acceleration cycle. This increases the momentum spread of the particles due to nonlinear filamentation, thus increasing the tune spread. This provides a smoother transition into the half-integer tune instability and increases the duty factor significantly.



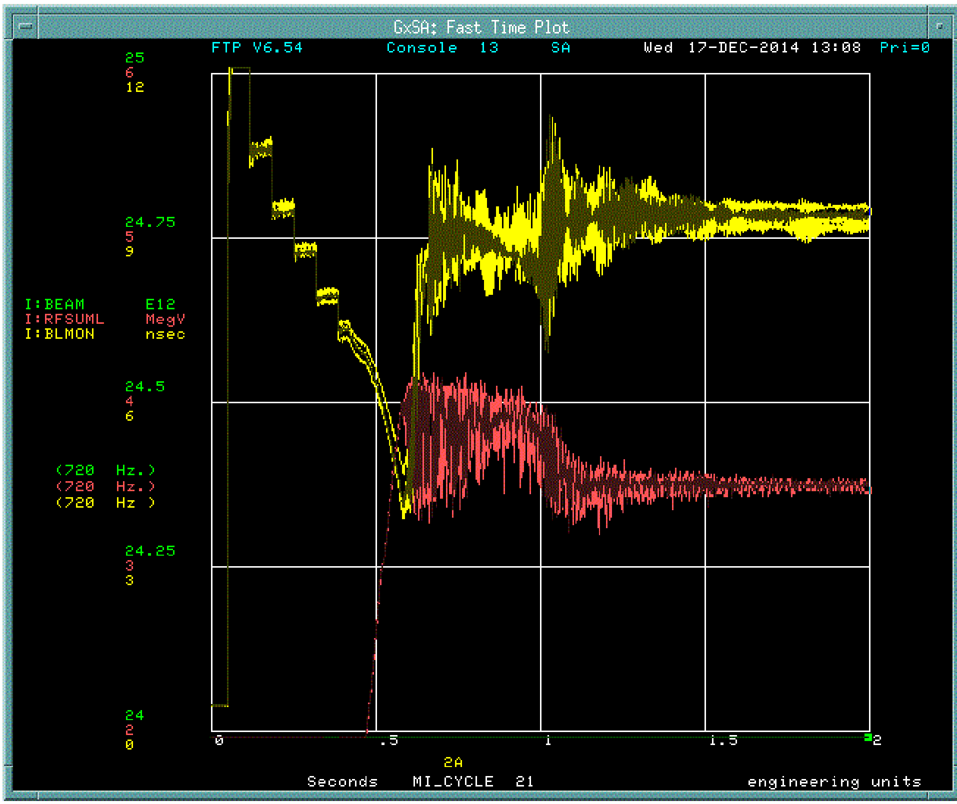


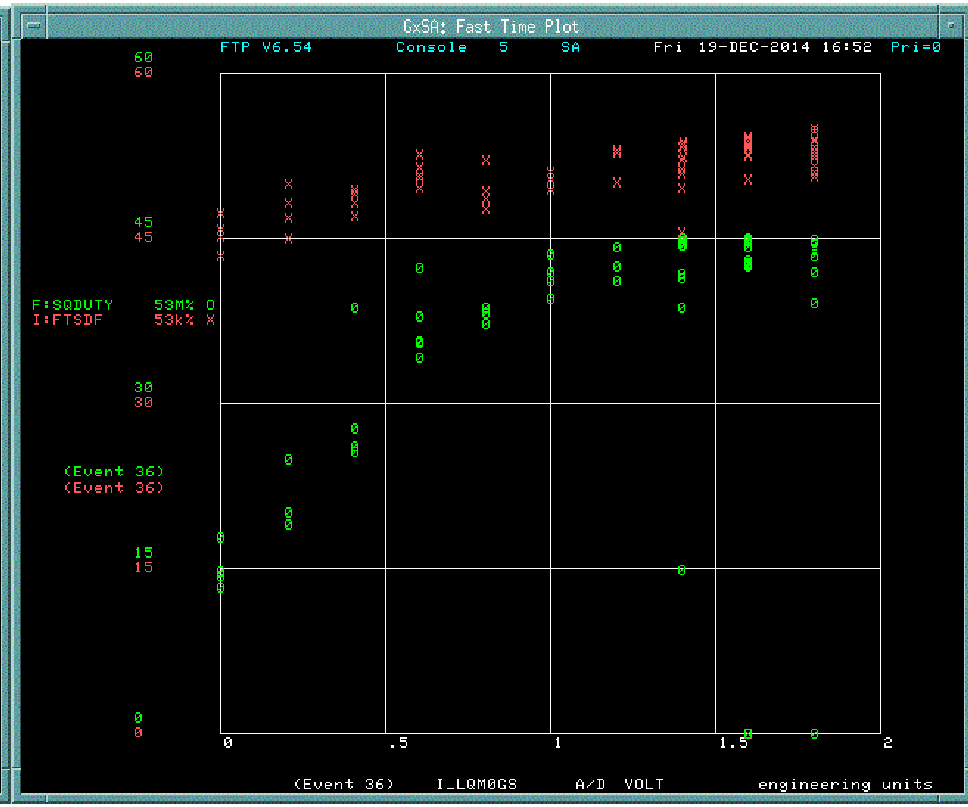
Longitudinal beam filamentation increases the momentum spread.

***Source*: Gerald Dugan, USPAS.**

Longitudinal fuzzing (quadrupole mode)

- Success increasing duty factor by driving quadrupole mode coupled bunch instability: ringing of bunch length after transition leads to increased longitudinal emittance.
- Non-zero chromaticity: increased longitudinal emittance means increased tune spread, more uniform spill





Source: MCR Elog

Problem:

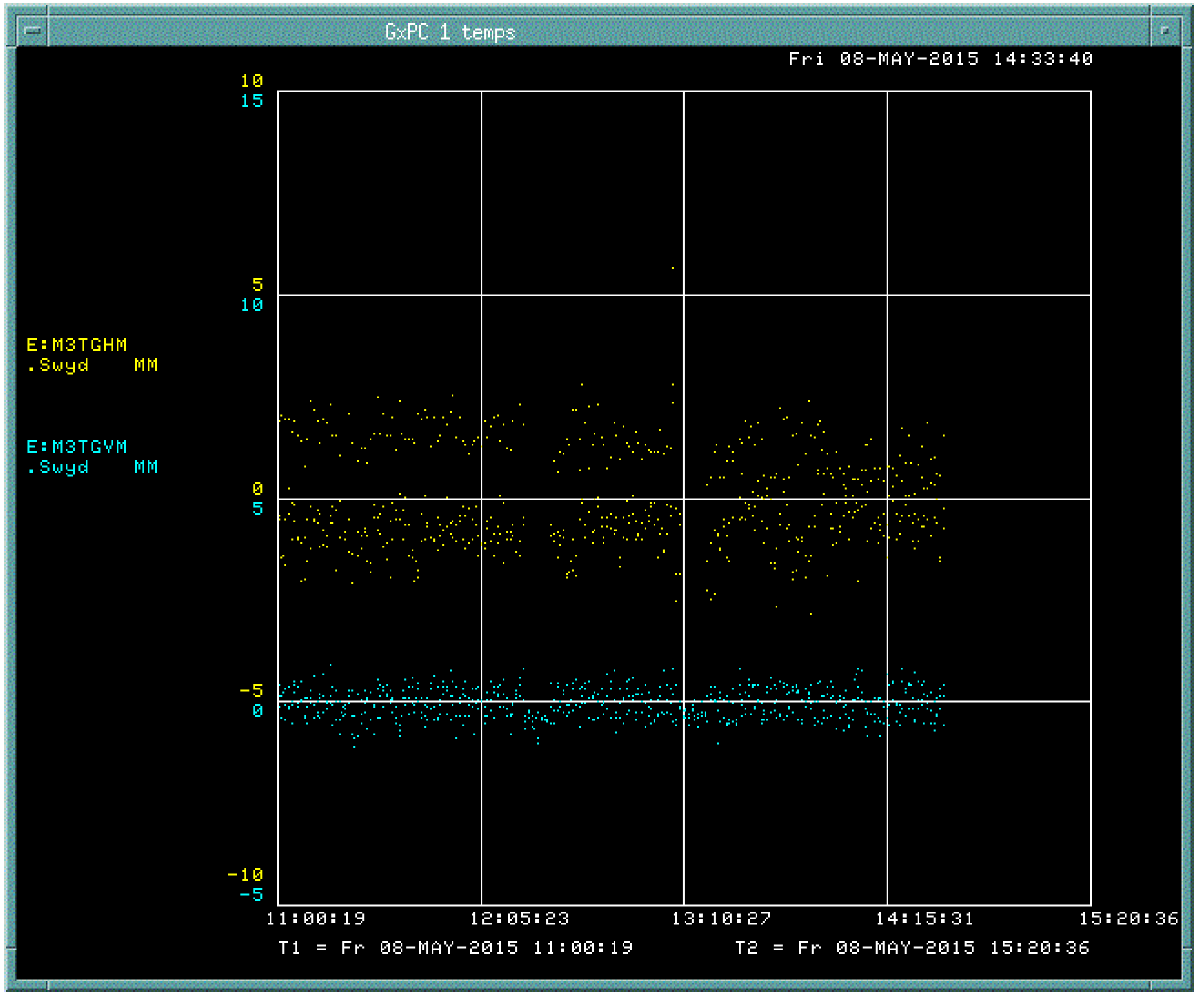
MI extraction loss, dispersive SY beam roll

Proposed solution:

Apply Hardt-like condition to balance chromatic effects of spill*

*New for ½-integer extraction?

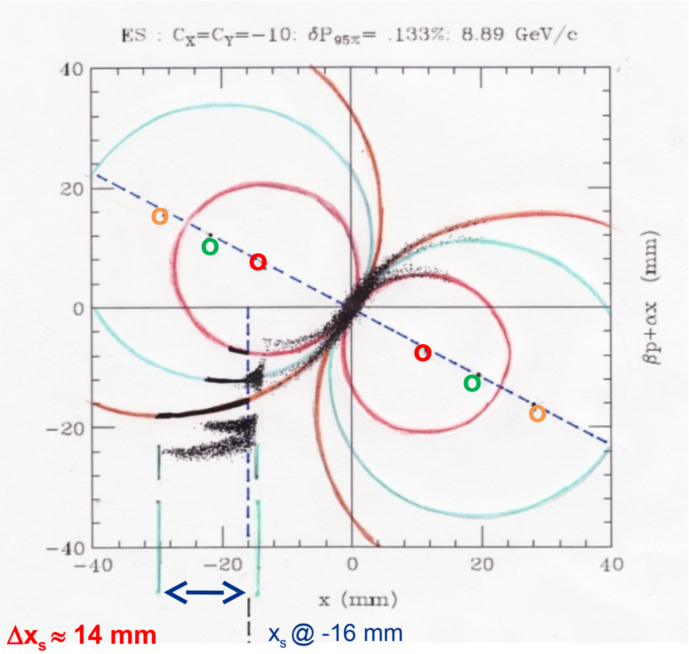
Beam roll @ SeaQuest target



Despite roll compensation ramps, beam roll of several mm remains. Compensation ramps must be periodically re-tuned if upstream conditions change.

MI spill is highly chromatic

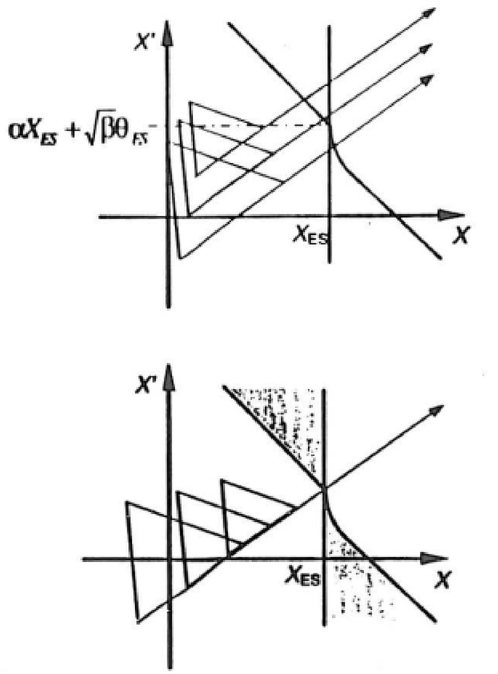
$$\left[x \pm \left(\frac{q_2\beta}{6\lambda}\right)^{1/2} \sin\left(\frac{\psi}{2}\right)\right]^2 + \left[x' \mp \left(\frac{q_2\beta}{6\lambda}\right)^{1/2} \cos\left(\frac{\psi}{2}\right)\right]^2 = \left(\frac{\Delta\beta}{6\lambda}\right)$$



Source: John Johnstone

High horizontal chromaticity is likely not optimized for consistent spill. Particles exit septa with angles highly correlated to their momentum. Leads to Lambertson losses and beam roll in beamlines.

Hardt Condition for 3rd integer extraction



Re-express the separatrix equation with *H* in terms of *Q'* and $\Delta p/p$

$$\left(X - D_n \frac{\Delta p}{p}\right)\cos(\alpha - \Delta\mu) + \left(X' - D_n' \frac{\Delta p}{p}\right)\sin(\alpha - \Delta\mu) = \frac{4\pi}{S} Q' \frac{\Delta p}{p}$$

To remove the momentum dependence from the separatrix, the equation below must be satisfied.

$$\boxed{D_n \cos(\alpha - \Delta\mu) + D_n' \sin(\alpha - \Delta\mu) = -\frac{4\pi}{S} Q'}$$

Source: Marco Pullia

Achromatic spill is a well-investigated problem for 3rd integer resonant extraction. The Hardt condition prescribes the balance between dispersion and chromaticity to produce achromatic spill. Possible for 2nd order extraction? We will also have a Q'' term due to octupoles.

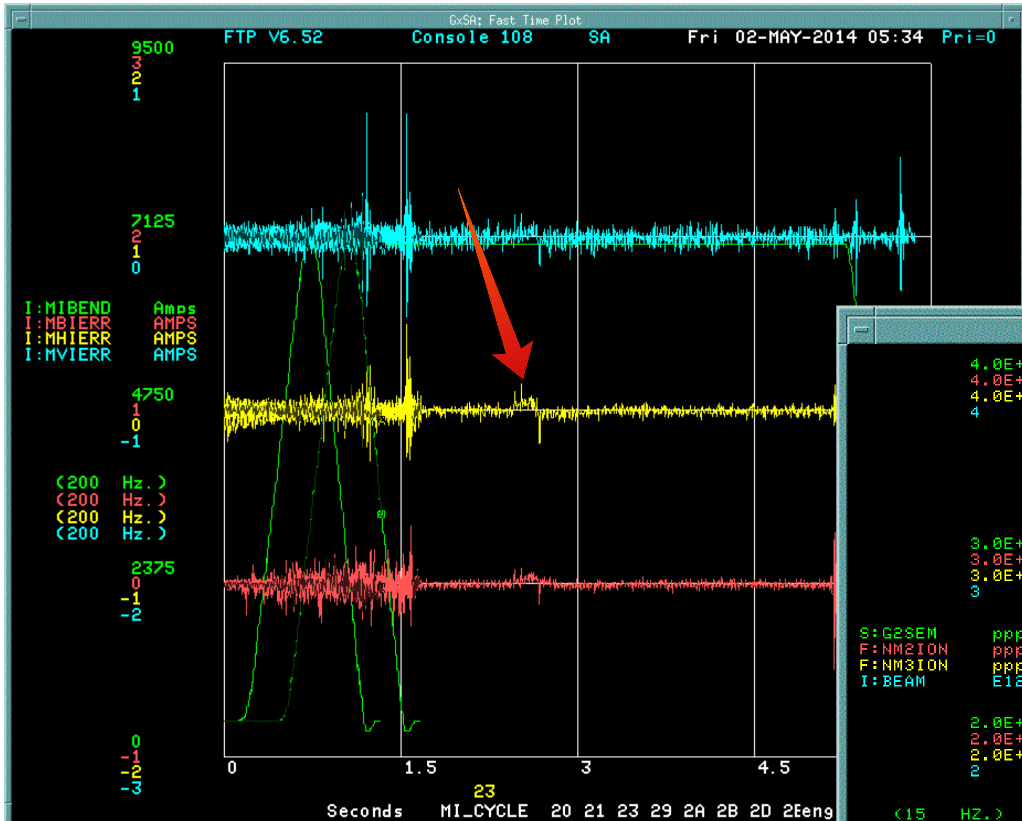
Problem:

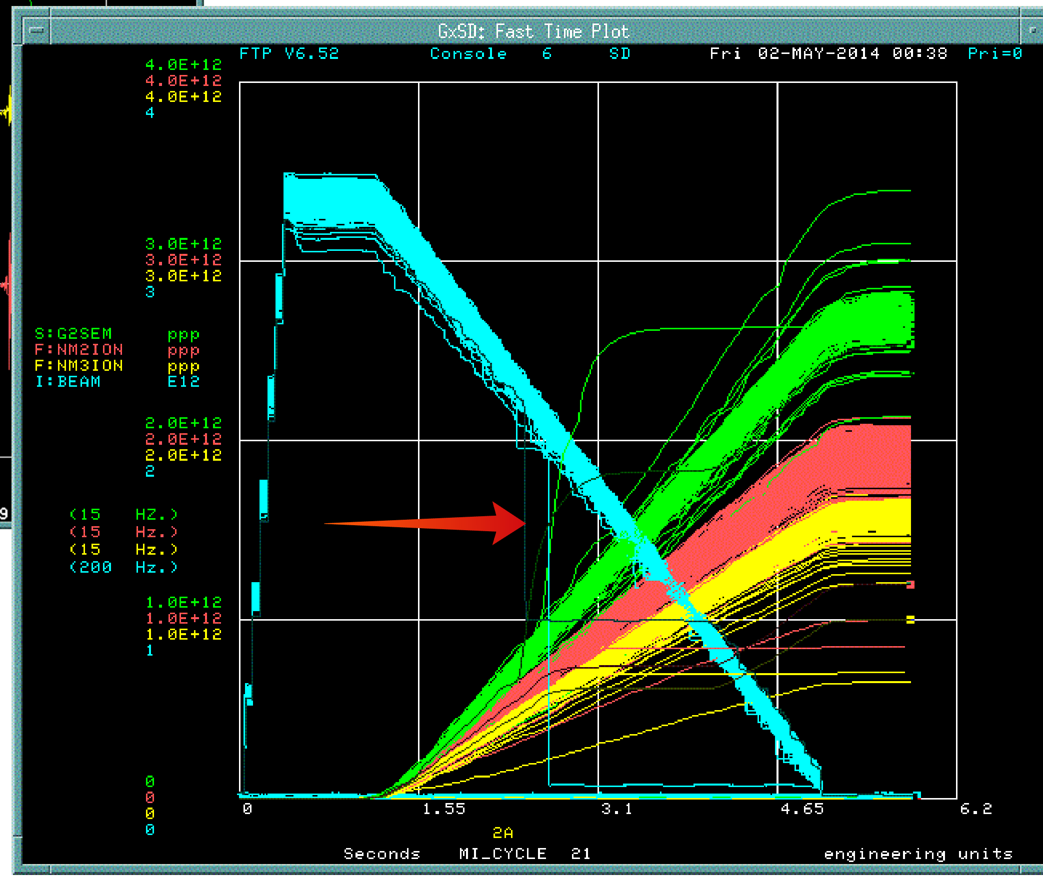
Occasional fast spills

Proposed solution:

Transverse fuzzing to let us back away from the ½-integer "cliff"

MI quadrupole bus errors





Source: 2014 MCR Elog

MI bus errors

- Errors either occur at random or when a new timeline is loaded (supercycle learning is cleared)
- These errors are withing the regulation specifications of the MI quadrupole supplies; i.e. we can't expect them to go away
- Quad errors *appear* to push beam tune up into the stopband, causing fast spill. Can re-create with MECAR tune tables?
- Dramatic increase in instantaneous beam power disastrous for experiments (E906, E1039...)
- Need spill scheme that reduces our susceptibility to these errors
- If we can operate farther from the ½-integer tune, we won't be so close to the instability “cliff”
- Increasing horizontal emittance should reduce the need for the ½-integer driving term, helping us run at lower initial tune
- Very time consuming, must re-program damper system to add new “fuzzing” state